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Toward renewable energy geo-information infrastructures: Applications of GIScience and remote sensing that build institutional capacity

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ABSTRACT

Sustained policy support is necessary in order to drive a transition toward renewable energy (RE). The ability to realize RE policy objectives is constrained by a range of geographic factors related to resource potential, the distribution of resources, land availability/suitability, the absorptive capacity of proximal infrastructure, and local socio-political acceptance. With this in mind, this paper provides a systematic review of how geographic information science and remote sensing techniques have been applied to reduce uncertainties surrounding renewable energy development, with emphasis on policy and planning needs. The concept of a 'geo-information infrastructure' is used to bring coherence and direction to this growing body of literature. The review highlights four underdeveloped research areas, including: Resolving issues of scalar discordance through comprehensive analysis at local and regional scales; mapping interactions in space of multiple supply options to deliver more accurate and sophisticated estimates of RE potential in an area and to identify competitive and symbiotic land-use situations; using energy resource maps as primary inputs into the development of technology road-maps; and developing geographically explicit indicators which can signal priority areas for RE recovery based on social and environmental returns on investments. In each case, suggestions moving forward are provided. The paper identifies knowledge-based institutional networking as a pathway through which local and regional public authorities can be equipped with the resources necessary to build and mobilize a geo-information infrastructure.

Contents

1. Introduction

Given the environmental impacts of fossil fuel production and use, increasing reliance on foreign energy supplies, and the depletion of easily accessible fossil and fissile energy resources,

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there is practical incentive to actively govern a transition to renewable energy (RE) resources including wind, solar, water, biomass and geothermal [1–5]. This transition is hindered by a number of barriers, however, including established technical and institutional preferences for incumbent energy technologies and public resistance to widespread deployment of RE [6,7]. The latter issue largely stems from the intrusion of new RE infrastructure on culturally and environmentally sensitive landscapes – for example, wind farms in typically agricultural or pastoral zones – combined with public perception that RE is a primary driver behind rising energy prices. Fortunately these barriers are not insurmountable, and they are at least partly linked to a common cause: A prevailing deficit of institutional capacity with which to achieve stated policy objectives within acceptable social, economic and environmental limits [8,9].

The ability of government to bring institutional capacity to bear on the transition to a RE future hinges on the quality of baseline information related to resource availability; technical capacity to recover energy from RE resources; and the risks associated with achieving stated policy objectives. There remains a lack of certainty at relevant political scales about the extent to which recoverable RE supplies can be sustainably procured to deliver energy services required by society, and of the capacity of existing technical and institutional systems to accommodate new infrastructure and resource management practices [10,11]. Compounding these uncertainties is the fact that a 'silver bullet' RE solution does not exist which means that governments must consider and incorporate an unprecedented range of resource and technology options in policy directives and energy planning [12]. There is a clear need for information management programs that can simplify the solution space while considering the conflicts that may arise with the increased integration of RE into existing landscapes.

Real RE potentials and conversion system designs are highly sensitive to geographical constraints on development as well as the regional political-economic context [13–17]. As such, integrating geographical information science (GIS) and remote sensing (RS) techniques with energy research has long been recognized in the academic community as critical to developing this baseline information [18–24]. Dominguez et al. [24] note that geographic information products possess numeric and cartographic value. Numerically, they can be queried to take stock of existing resources within an area and/or they can deliver spatially accurate inputs into econometric or engineering analytical frameworks at a variety of geographic scales (from a particular site to a regional or global assessment). As cartographic products they provide easily comprehensible communication devices for policy advice and public relations. Additionally, as data-storage costs decrease, and as our understanding of cyber-infrastructure and ways to extend the reach of digital information increases, geospatial technologies offer significant opportunities for direct collaboration with a broad range of stakeholders through web-mapping and participatory GIS [23,25].

With this in mind, this paper proposes that a 'geo-information infrastructure', described here as the deep integration of GISystems and remote sensing into decision support and information management [152], can help to rectify the information deficit surrounding RE. A geo-information infrastructure has three primary components: (1) the *data domain* which includes input functions related to data acquisition procedures, data storage within a flexible and interoperable geodatabase, and data preprocessing techniques to ensure that data are structured to meet end-user needs; (2) the *analysis domain* which includes the GISystems that can synthesize these datasets within a single analytical framework, and the geospatial concepts and techniques (i.e., GIScience) to process these datasets; and (3) the *communication domain* which includes output functions related to all derived geographic information products. Figs. 1 and 2 illustrates the broad contours of this information management model and how it can be leveraged for decision support to expand institutional capacity through data sharing, knowledge generation, knowledge transfer, and collaboration with various stakeholders.

In fact, a RE geo-information infrastructure is already being developed in some jurisdictions. In the US, the National Renewable Energy Laboratory (NREL) and the Oak Ridge National Laboratory (ORNL) are highly active in the development of energy maps and other tools for the spatial analysis of RE. Canada's Federal Ministry of Natural Resources (NRCan) has published online energy maps for solar and wind resources, while Agriculture and Agri-Food Canada has released the Biomass Inventory Mapping and Analysis Tool (BiMAT). Canada's federal government also sponsored the development of RETScreen, a freely available system-analysis software that draws from a wealth of underlying spatial data to determine primary inputs while providing decision-support for a prospective developer and investor at the pre-feasibility level. CIEMAT, an energy and environmental research group based in Spain, has developed a stand-alone RE spatial analysis system called IntiGIS which is currently used as a primary decision-support tool in a number of Latin American countries seeking to develop sustainable energy policies [26].

With all of this in mind, the objectives of this paper are twofold. First, the concepts and techniques that are currently used to generate geo-information related to RE potential and deployment are assessed. The focus here is on issues related to policy and planning including resource inventories; site assessments and the generation of spatially explicit supply-cost curves; and spatial planning of RE infrastructure. Second, the paper identifies ways in which existing research techniques can be leveraged, improved, and unified to maximize the ability of geo-information infrastructures to increase institutional capacity in the RE domain. Four general underdeveloped research areas are identified here: resolving issues of scalar discordance by identifying a scale of analysis conducive to effective resource inventorying, monitoring, and knowledge transfer; mapping interactions in space of multiple supply options to deliver more accurate and sophisticated

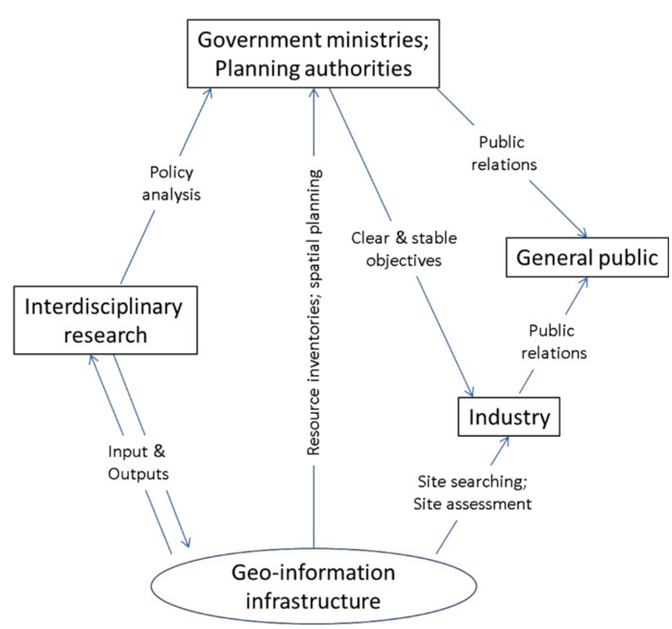


Fig. 1. Communication links between key stakeholder groups made possible through a geo-information infrastructure.

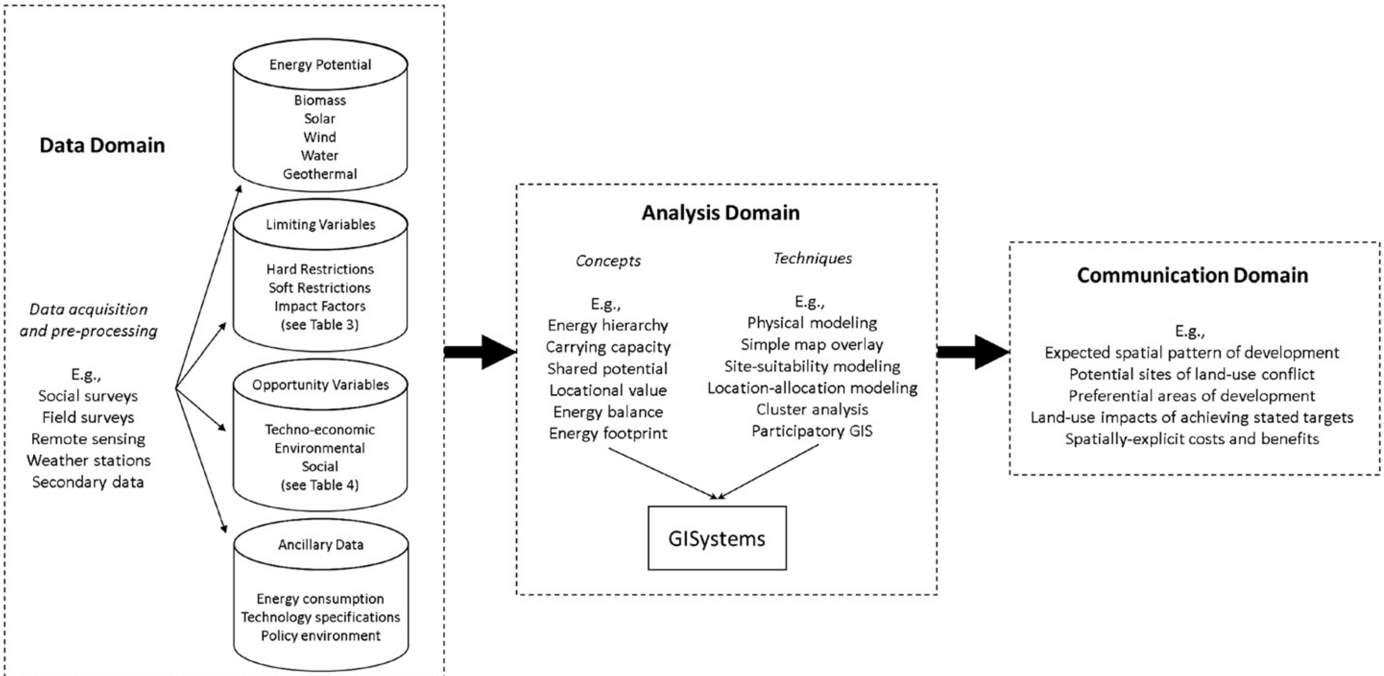


Fig. 2. The primary components of a geo-information infrastructure, with selected examples of key concepts, techniques, and information products

estimates of RE potential in an area and to identify competitive and symbiotic land-use situations; using energy maps as primary inputs into the development of technology road-maps; and developing geographically explicit indicators which can signal priority areas for RE recovery and therefore suggest a pattern of development that more closely approximates an optimal situation in accordance with broader policy objectives. The paper concludes by discussing knowledge-based institutional networking as a pathway through which public authorities can be equipped with the resources necessary to build and mobilize a domestic geo-information infrastructure.

2. Progress in RE mapping

Conventionally, RE mapping exercises have been focused on site-suitability through a top-down approach to locating and quantifying resource potential [18,21]. Analytical frameworks begin by identifying the physical factors which determine the scale and intensity of RE over the landscape – i.e., the 'theoretical potential' – and then include various social and technical restrictions from which to distinguish resources that can be accessed and converted at a reasonable cost—i.e., the 'technical' and 'economic' potential. The review of progress in RE mapping conducted below is structured around this hierarchical logic.

2.1. Resource inventories: Modeling the geographic distribution of theoretical RE

Locating and estimating theoretical RE potential involves a search for physical expressions of a reproductive surplus of useful energy. In other words, mapping theoretical potential is a resource-oriented task and is therefore often referred to as measuring the 'physical limit', because this category considers only how geophysical properties dictate the scale and intensity at which a resource is able to 'do work' [27]. These aspects include solar irradiance; wind speed and density; biomass density and distribution; range and rate of change of sub-surface vertical temperature gradients; wave frequency and structure; tidal ranges; and the structure of a hydrological 'choke-point'. The form, timing and intensity of RE are sensitive to site-specific variables related to land cover, latitude, altitude, climate and terrain. Energy process modeling techniques draw from fundamental research in geophysics and Earth science, and more specifically climatology, meteorology, geomorphology, geology, and forestry, to relate these variables to theoretical energy potential [21,28]. The derived information forms the basis of RE inventories within an area, and represents the crucial first step in the energy mapping process.

Primary spatial data acquisition and modeling are critical to the inherent quality of the information derived from these geophysical process models in terms of accuracy and precision, and to the ability of this information to meet the expectations of the user [29,30]. One of the primary data properties to consider during the data acquisition phase of a GIS project is the spatial properties of the dataset relative to the resource of interest in terms of its basic spatial unit and areal coverage. Spatial data are ideally structured to reflect the spatial qualities of the geographic features of interest [29]. Two general spatial data models are used in GIS and must be considered when formulating a broad research program or specific research project: the vector and the raster data model. The former is an object-oriented data model. The basic units used to represent observations in space are points, lines, and polygons in a way that most closely relates to 'classic' cartographic techniques, with thematic information related to specific features in an underlying attribute table. The latter is a grid model composed of a set of unique values arranged in tabular format. The basic unit used to represent observations in space is a cell with a specific resolution (areal dimension), whereby each cell value represents a feature or theme of interest. The raster model is especially useful to measure 'field variables' which are continuous or diffuse geographic features that lack rigid boundaries and which can be measured at every possible point within the study area. Raster data are also best for efficient and accurate overlay modelling which is critical to identifying restrictions to primary resource use (see Section 2.2), and are the primary

Table 1
Application of remote sensing methodologies to locate and estimate renewable energy potential.

RE resource	Remote sensing methodology	Literature source
Geothermal	Mapping thermal anomalies using thermal infrared wavebands available from LANDSAT 7 and ASTER satellite systems	[33,34]
	Hyper-spectral image classification to identify minerals and vegetation stress associated with near-surface geothermal venting	[33,35]
Hydro	Using false-color composites to map hydrological regimes. These must be evaluated in the context of topographical measurements to identify 'choke points' at which optimum reservoir height and size can be achieved. Images are classified to identify the surrounding land cover and land-use types potentially affected by flooding patterns	[36,37,38]
Solar	Review time series of satellite images to empirically measure annual cloud cover to determine quantity of solar energy reaching lower atmosphere	[39]
	Absorption of high energy electromagnetic wave bands measured via high radiometric resolution sensors used to characterize earth-atmospheric reflectivity and detect levels of atmospheric turbidity	[40,41]
	Object-oriented image recognition to determine available rooftop area suitable for solar photovoltaic deployment in urban landscapes	[42,43]
	LiDAR data classification used for highly accurate irradiation mapping at the urban scale by modeling annual and monthly irradiation incident on building facades given shadowing and reflectivity from nearby objects	[44]
Wind	Scatterometers and synthetic aperture radar systems map off-shore wind energy by measuring backscatter intensities from sea surface roughness as an indirect way of measuring wind speed and direction	[45]
Biomass	Bioenergy analyses draw from established methods in forestry and agricultural science to identify structural and floristic characteristics which help estimate extractable volumes of biomass and to identify the biochemical characteristics which are relevant to biomass-to-bioenergy conversions (e.g., the distinction between hardwood and softwood species)	[46,47]

output of remote sensing techniques which allow data acquisition to extend beyond reliance on low density and small area data such as weather stations or site surveys.

The distributed, low-density, and often remote nature of many RE resources has instigated a trend toward remotely sensed (RS) data and the use of raster data structures; what Wang et al. [31] qualify as a 'new way of thinking' about energy analyses; see also [32]. For illustrative purposes specific examples of applications of RS to energy research for a broad range of RE sources are listed in Table 1. For the most part, these methods do not measure RE potential directly. In some instances, RS techniques quantify measureable parameters that are subsequently soft-linked to external (spreadsheet) software packages to run a physical model, or are used as input layers into GIS-based physical modeling (e.g., the *r.sun* package in GRASS). Alternatively, RS methods can measure phenomena that are spatially correlated with a potential source option and therefore identify the existence of an energy resource rather than explicitly estimate a physical potential. The separate methods identified for geothermal resources in Table 1 are exemplary of this distinction.

Although resource inventories are increasingly based on aerial or satellite RS tools, ground-based measurements are still used extensively and are necessary for RS data validation and triangulation. Agencies such as NASA and NREL continue to maintain a significant network of ground-based measurement devices including radiometers/pyranometers and anemometers to measure solar irradiance and wind speed respectively at specific sites [21], while buoy measurements remain the dominant source of data from which to derive wave energy potential [48,49]. In many cases, national forest and agricultural resource inventories are still derived primarily from a combination of ground surveying and manual interpretation of air photos to gather information related to biomass resource supply [50]. Nygaard et al. [51] demonstrate how some of these datasets are requisite to performing a rapid and more accurate assessment of theoretical energy potentials over a wide area, even when RS data are available. In fact, ground-based data are often more precise and comprehensive, in the sense that a wider range of physical attributes can be measured simultaneously. In this case, the attribute handling capacity of vector data structures is useful for mapping energy sources where energy yields are subject to a number of spatially-specific parameters; e.g., topographical and hydrographical characteristics that determine the power of falling water including head-height and the volume and density of the water column [52]; feedstock characteristics including moisture content and particle density that determine the viability of using secondary biomass from industrial processing plants or livestock manure [53,54]; and the depth and geological structure of geothermal wells [55]. Each of these variables can be stored as fields in an attribute table within a vector dataset and then related through a physical model to estimate energy densities at these sites. In contrast, the raster data structure would require multiple raster layers and the use of raster algebra to store and process the same information.

Building on this discussion, Table 2 lists the spatial qualities of various RE resources, including aspects related to form, mobility and spatial distribution, and the spatial data model that best suits these qualities. It is important to note that this table is based on ideal situations, and in fact user requirements and data limitations might result in a divergence from this guideline. Generally, raster-to-vector and vector-to-raster data conversions; spatial interpolation and extrapolation; and 'merging' techniques are employed to in the pre-processing stage of geospatial analysis to change the spatial properties of a dataset in terms of model and extent to fit the hands of the user. A recent example of this can be found in [56] where 'feed forward' artificial neural networks are used to estimate wind energy at un-sampled locations in hopes of developing a model that could deliver an accurate continuous (raster) wind-speed dataset from site-specific (vector) measurements using irregularly sampled anemometer data. Furthermore, data synthesis and data triangulation techniques can be employed to extend the areal coverage of a dataset. It is important to recognize, however, that the quality of indirect datasets – i.e., those datasets derived from controlled pre-processing techniques – relative to their source datasets is difficult to assess, especially in terms of data accuracy. These techniques can therefore introduce uncertainty into the analysis and are best avoided, but when necessary it is vital to perform intensive and advanced data quality assessments to understand error propagation and to communicate known uncertainties.

2.2. Modeling constraints to RE resource accessibility

The real potential of RE is only a fraction of its theoretical potential. The process of estimating actual RE potentials in a given area must therefore include an analysis of all limiting variables. Following [57], these variables are categorized here as 'restrictions' and 'impact factors'. Spatial data overlay and map algebra techniques can be used to integrate these variables to yield a map which identifies locations that have a combination of

Table 2
The spatio-temporal qualities of various RE sources. Information compiled from [13] with data structure considerations from [29]. 'Immobile' refers to the fact that the resource cannot be converted into useable forms of energy beyond the immediate site. Note that 'direct' biomass refers to above-ground forest and agricultural material and associated residues while 'indirect' biomass refers to industrial process residues and municipal and animal organic wastes.

RE resource	Spatio-temporal qualities	Data structure
Solar	Continuous; distributed/extensive; immobile; intermittent and unpredictable	Raster
Wind	Continuous; distributed/extensive; immobile; intermittent and unpredictable	Raster
Wave	Continuous; distributed/extensive; immobile; intermittent and unpredictable	Raster
Biomass		
Direct	Discrete; distributed/extensive; mobile; controllable	Raster
Indirect	Discrete; concentrated/intensive; mobile; controllable	Vector
Tidal	Continuous; distributed; immobile; intermittent and predictable	Raster
Geothermal		
Vents	Discrete; concentrated/intensive; immobile; controllable	Vector
Near-surface heat	continuous; distributed/extensive; immobile; controllable	Raster
Hydrological	Discrete; concentrated/intensive; immobile; controllable	Vector

Table 3
Synthesis of spatial constraints on RE development. Compiled from various sources.

Criteria	Restrictions		Impact factors
	Hard	Soft	
Environmental/ecological	Land area; land accessibility; land cover type seismic instability; extreme slope; extreme altitude; extreme climate	Natural reserves; species habitat reserves	Slope; aspect; land cover type; latitude; climate; altitude; soil type; water depth (bathymetry)
Technical/economic	Proximity to water; proximity to airports (electromagnetic interference)	Extreme distance to distribution infrastructure; extreme distance to demand; land contiguity for system development	Distance to infrastructure (road, rail, wires, pipes); proximal infrastructural capacity and stability (e.g., local bus load)
Social/political		Culturally sensitive areas; Minimum set-back requirements of infrastructure; land use (zoning laws)	Land ownership; land value; population density; distance to urban area

characteristics making them suitable for RE development e.g., [58–62]. These mapping techniques are used to establish fuel-mix quotas that consider limitations to RE recovery in the management area [24]. At the level of policy implementation or project pre-feasibility, these methods can be used in the 'site searching' process to locate optimal sites for development e.g., [151], and in fact if this information is made publicly available it could facilitate investment decisions by drastically reducing the time required to search for an acceptable location for development. Using a review of various sources Table 3 provides a list of relevant geospatial variables which place limits on RE recovery and which influence site decisions related to RE development. The distinction within and between restrictions and impact factors is important, and there are a number of ways in which these variables can be used to derive geo-information about resource accessibility.

Restrictions are criteria that automatically eliminate a site as a potential supply point in the analysis. Within this category one can distinguish between 'hard' and 'soft' variables [21] to reflect the difference between locations where energy recovery *cannot* occur due to absolute limits and locations where energy recovery *should not* occur due to prevailing institutional and infrastructural conditions. In other words, 'hard' restrictions are for all intents and purposes fixed and indefinite and therefore define the sites at which energy recovery is not physically or technically possible while 'soft' restrictions can be more readily overcome through technical innovation, infrastructural development, or changes to legislation, land-use patterns, and cultural attitudes. The latter distinguish sites at which energy recovery is politically unacceptable or technically cumbersome, but not impossible. The analyst has some discretion in terms of whether or not to make soft restrictions exclusive; the alternative is to adjust the relative influence of these variables to perform scenario analyses or to run a sensitivity analysis based on forecasting political decisions (e.g., allowing RE development on increasingly higher value agricultural land), social change (e.g., reducing wind turbine setback distances from residential zones due to broader acceptance of their intrusion) or technical development (e.g., expansion of the electricity grid, pipeline network or transport system). Ultimately, analysts can look to broader land-use policies and regulations or seek input from users and citizens within their study area to make determinations about how best to categorize and incorporate a spatial restriction within the analytical framework.

In any case, restricted sites are often located, sized, and eliminated in analytical frameworks by way of simple geoprocessing techniques, including 'buffering', 'clipping', 'masking', 'erasing' or 'reclassification' [see [30] for a discussion of these techniques in the context of resource management]. An important insight drawn from such analyses is that, commonly, constraints which restrict land availability alone reduce the physical availability of land potentially devoted to energy production by at least half [63,154]; the land that is remaining defines the area's RE 'carrying capacity' and ultimately the potential for RE production within an area [57].

In contrast to restrictions, impact factors are geographical attributes that eliminate a site as a potential supply point only if some threshold is reached. They are variables that structure the degree to which a potential resource is technically and economically recoverable for energy end-use at a particular site. Impact factors can be mapped in a number of ways. Most commonly, they are represented on an ordinal scale to measure their impact on the 'suitability' of a site for energy recovery, with a value of

0 or 'NoData' indicating that a threshold (i.e., restriction) was reached and therefore the site is not suitable at all, and the highest value on the scale indicating that the site is ideal based on its specific characteristics. Terrain and topography expressed as slope offers a useful example. A flat surface is more suitable for biomass extraction, wind turbine deployment, and energy distribution infrastructure development while a slope nearing 20 or 30 degrees makes it increasingly uneconomical or physically impossible to perform any of these tasks [60,62,64]. Using data reclassification techniques, measurements of slope can be inputted into mutually exclusive and collectively exhaustive bins of successive measures of compatibility: e.g., with 0–3 degree slopes being most suitable and therefore reclassified as the highest value on the scale; 28–30 degree slopes as being least suitable and therefore reclassified as a value of 1; values in between divided amongst the remaining bins; and all values over 30 degrees reclassified as 0 or 'NoData'. If all relevant input variables are reclassified accordingly, map algebra can be used to develop a multi-criteria evaluation site-suitability wherein the values are summed and the highest output values indicate the most suitable locations within the area. Impact factors can also be assigned varying weights in situations where one input variable holds greater influence and can therefore compensate for other input variables, as in the analytical hierarchy process and weighted sum analysis e.g., [52,63,65,153]. Given that impact factors and decision criteria rarely follow crisp boundaries, fuzzy quantifiers are also used, in which case variables are represented as real numbers to a pre-specified precision rather than as integers or whole numbers [66].

Using the techniques discussed above, energy maps classify locations by their degree of suitability relative to some 'ideal' situation. There are two alternatives to these techniques. First, impact factors may be equally valued via the Boolean operation 'AND', in which case all conditions must hold for a site to be identified as 'suitable', or what Nguyen and Pearce [67] call 'candidate sites'. In this case, every location is classified as either suitable or not using binary logic rather than falling within a gradient of suitability. Second, map overlay and algebra techniques can be used to derive quantitative rather than qualitative conclusions about resource accessibility. Impact factors must first be re-classified using an economic function (e.g., $/km from distribution infrastructure to account for connection costs) or a physical function (e.g., a fraction of biomass recovery from an agricultural field per degree slope to consider soil erosion) depending on the specific factor and resource involved, rather than on a gradient from 'worst' to 'best' or into binary format as 'suitable' or 'unsuitable', as is the case above. This form of arithmetic re-classification is essential to the development of geographically explicit supply-cost curves, as in [68,155].

In most of the cases discussed above, the assumption has been that the location of the RE source is also the location where electricity or heat will be generated. Bioenergy is unique in this respect, given that biomass is a stock of RE that can be transported in its raw form so that aspects of bioenergy production are distributed throughout space rather than concentrated at the site of resource occurence. This adds the element of feedstock transportation into the analysis. In most cases, transportation costs are the primary constraint for bioenergy development in an area thusly presenting a constrained-optimization problem solvable through location-allocation modeling [53,69]. If high quality transport infrastructure data are available in vector format, factors related to transportation costs are included into the analysis through network analysis with further restrictions related to speed and hauling capacity coded as attributes that influence the movement of material across the landscape [70,71,155]. If, on the other hand, road infrastructure data are unavailable or if (access) transportation infrastructure has yet to be developed, a winding coefficient or tortuosity factor can be applied to simple straight-line distance calculations between a resource origin and the prospective site for conversion [72].

A common mistake with constraint-based analyses is a narrow pre-occupation with site-suitability and a lack of consideration toward the 'hidden costs' associated with RE development. In fact, the capacity of an area to support RE development is not only determined by land area and site suitability, nor is a resource exploited simply as a function of its existence or economic merits. Chief among the hidden costs within an area are geotechnical variables related to the technical absorptive capacity of proximal infrastructure, defined here as the ability of local infrastructure and demand structures to accommodate new capacity or system expansion, ideally with minimal overhead and minimal impacts on current system functions. In the electricity sector specifically, the most important variable is the state of local distribution infrastructure with respect to capacity on the grid and the ability to accommodate voltage contingencies associated with intermittent resources such as solar and wind [62]. Site-specific data on access points into distribution infrastructure are best classified as soft-restrictions since any restrictions can be overcome through investments into system upgrades. System-level restrictions are often difficult to assess with a high degree of certainty, however. In many cases, spatial data on the status of a distribution network is proprietary due to security issues or is buried in an administrative and bureaucratic matrix and can therefore be difficult to access. Another important geo-technical variable is the sustainable water yield of an area [10]. Water availability needs to be included as a hard restriction to the development where water-intensive bioenergy systems (e.g., to generate steam in the case of heat and electricity or to facilitate hydrolysis in the case of biofuel production) are being considered.

2.3. Bringing local knowledge to geo-information infrastructures

The political absorptive capacity of an area is shaped by local sentiments toward infrastructure expansion or facility siting that may stall or prevent the development of an otherwise economical resource. While detailed mapping can eliminate all locations unsuitable because of physical, technical, and economic constraints, there is no universal process for defining the impacts of these preferences on RE potential and infrastructural development [75], although as noted above it is standard practice to immediately restrict development on ecologically or culturally sensitive landscapes to avoid obvious conflict. Some analysts utilize 'viewshed' analysis, 'population density', or 'distance to population centers' as indirect metrics for assessing amenity impacts and the likelihood of local resistance to the development of a particular site [76,77]. Van Hoesen and Letendre [61], however, argue that direct community input is the only way to enhance our understanding of these local restrictions on system deployment and therefore resource use.

Incorporating participatory mapping exercises into the RE deployment process is a useful tool to identify socially optimal patterns of investment and in guiding spatial planning of system deployment [61,78,79]. Participatory techniques can be distinguished based on whether they are used as part of the creative process in energy mapping and spatial planning, or used as the basis of feedback on existing plans. Citizen survey techniques enable a broad range of stakeholder input in terms of the variables that should be included and the weights that should be applied to specific siting variables that are included in energy mapping efforts (see [25] for further elaboration). Similarly, interactive web mapping applications offer the ability to allow individuals or groups of users to independently drive the mapping

process as a way to offer community input. Rojanamon et al. [80] employ a questionnaire survey and focus group discussions to perform a social impact study *after* the most feasible sites for RE development in their study area were located through expert analysis. In fact, through social surveying techniques [81] found that the 'most suitable' location based on an expert techno-economic analysis was perceived by the general public and other stakeholders to be a 'moderately suitable' location.

2.4. Summary

Geographic information technologies have been used to answer questions at three levels of RE decision-support: the strategic level through the establishment of realistic fuel-mix directives as supported by geo-information of technical energy potentials or an area's 'carrying capacity'; the tactical level via planning and implementation of public procurement programs as supported by site-suitability analysis including aspects related to the technical and political absorptive capacity of an area; and the operational level via specific project development as supported by geographically explicit supply-cost curves and more detailed analyses of site-suitability through high precision data which consider the 'hidden costs' related to RE development. Ultimately, the form, precision, and scale of the analytical framework are dependent on the intended end-use of the information. The following section highlights key research areas which need to be addressed to maximize the practical value of mapping exercises within the RE policy and planning domain.

3. Directions in RE mapping: Issues for policy and planning decision support

Better decisions can be made through better mapping. Although the previous section highlighted some key areas that have been engaged through the integration of GIS, RS and energy research, a number of deficiencies still need to be addressed at the strategic and tactical level. This section focuses on four of the most pressing issues: (1) issues of scale discordance that embed uncertainty into baseline data and prohibit communication of information to a relevant audience; (2) insufficient attention to the potential for system-level synergies based on the co-location of resource options; (3) a lack of 'pre-screening' metrics that consider issues related to land uptake; and (4) failure to suggest optimal spatial patterns of development based on opportunity investments within the management area. In what follows we identify key geospatial concepts and techniques that can help address these gaps.

3.1. Selecting appropriate scales for data collection and communication

The first step in the energy mapping process and in the development of a geo-information infrastructure more generally is the identification and delineation of the area of interest. This step requires careful consideration because, generally speaking, the way in which space is partitioned for analytical purposes has an impact on the outcome and the usefulness of the analysis. Certain areas may be favoured due to a high concentration of resources simply as a function of the way in which data are aggregated ('aggregation effects'; see also [32]), while limiting the analysis to a specific area may not fully appreciate the potential contribution of resources that lie immediately beyond study boundaries ('boundary effects'). The problem of identifying the correct study area, including the spatial extent, minimum mapping units, means of spatial data aggregation, and location of analytical boundaries, is known in the geographic literature as the modifiable areal unit problem (MAUP) [82]. The MAUP is a persistent problem, meaning that it cannot be fully resolved, only mitigated. Furthermore, an 'optimal' scale of analysis is context-specific and generally a function of study limitations related to funding, data availability, and established institutional practices and configurations. Recognizing these limitations, this section attempts to identify the factors which need to be considered when selecting the unit of analysis and delineating analytical boundaries for a mapping exercise aimed at energy policy and planning decision support. These factors include the scale of RE operation and the scale at which RE systems are best organized and managed.

Renewable energy systems are site specific and regionally confined, meaning that supply chains are either concentrated at the site of resource occurrence or are highly localized [14,15]. With the exception of small quantities of bioenergy, RE resources are not globally traded and it is unlikely that a given area will be able to rely to any significant degree on the RE resources of a distant area. In other words, RE systems operate predominantly at local scales. The scope of the analysis must be structured accordingly. Large-scale analyses increase the minimum mapping unit and therefore rely on the use of aggregated data whereby average values are privileged over spatial distributions. This fails to fully appreciate the geographic nuances that structure RE resource availability and system performance. Indeed, spatial resolution of data inputs is the primary limiting factor to the accuracy of geospatial analysis of RE potential [22,61] which helps to explain the fact that estimates of RE potentials at the global scale vary by one or two orders of magnitude due largely to uncertainties related to local geographical nuance [83–85]. Even national-level assessments, for example those coming out of the US, can yield entirely competing views about the extent to which RE can satisfy national demand [86,87]. While perhaps useful for developing global consciousness and healthy debate, this variance is entirely unacceptable at the level of policy development and implementation. The uncertainty embedded in coarse resolution data and large-scale analyses is clearly an insufficient baseline upon which to develop informed discussion, let alone the inventorying and monitoring programs that are vital to successful RE procurement programs. Smaller scale analyses, on the other hand, are able to limit the assumptions required in order to derive reliable conclusions.

Energy production and consumption is inherently territorial. The unit of analysis must therefore reflect the scale at which potential energy resources are politically managed, so that the results are communicated to an audience who is willing and able to incorporate the findings into active policy or into concrete investment. It is important to recognize, however, that management does not always occur at the national scale. In fact, to more closely align the scale at which RE operates with the scale at which they are managed, nations have begun to decentralize authority over RE supply and planning decisions see [88–94]. Local-level jurisdictions clearly want a greater sense of autonomy in energy planning and in many countries, Canada especially, there is a growing number of 'community energy plans' being developed at the municipal level [91,92].

Information management must respond to these trends in energy production and energy governance: Just as RE technical operations and political authority have decentralized, so too must RE analyses. A review of literature, however, reveals a problem with scalar discordance: i.e., the scale of analysis is not reflecting the (optimal) scale of management. Mapping exercises continue to privilege the global or international level e.g., [19,22,32,50,68,95,96], and researchers have cited a noticeable absence of

studies which employ integrated analyses at regional scales thereby failing to connect local energy analyses and planning to national or global energy analyses and planning [21,97,98]. This is problematic for the institutional capacity of RE governance regimes, since scalar discordance in knowledge resources and a lack of knowledge transfer are among the primary barriers to effective governance [99].

Organizing and managing an efficient energy system which incorporates RE is a matter of understanding the interconnections between available resources, existing infrastructure and land-use patterns, consumer demand profiles, and constituent preferences for energy futures that both constrain and enable the recovery of energy from particular resources at particular sites. While community or municipal level analyses engage these issues at a very high resolution e.g., [153], in almost all cases, a city cannot be energy self-sufficient based on resources derived from within city boundaries; all urban areas will have a supply-shed that is proportional to the energy demand of that city and since energy consumption is far more concentrated than energy demand this supply-shed extends beyond the boundaries of the city see [156]. This supply-shed may overlap with that of an adjacent or proximal city, so that as carrying capacities are constrained and land becomes scarcer, community energy plans will no longer be capable of developing independently of each other. In other words, the most important issues surrounding the integration of RE into existing energy landscapes are inherently 'regional' or 'inter-municipal' questions. To solve issues of scale discordance in RE mapping, it is therefore prudent to mobilize geo-information resources at the regional scale. Adjacent regions can then be modeled as 'sinks' (net consumers) or 'sources' (net producers) of energy.

The merits of regional-level energy mapping are well established in some aspects of the literature. In fact, many analysts have already demonstrated the adequacy of the regional scale as a practical unit of analysis for renewable energy inventory and monitoring [100–103]. Sarafidis et al. [104] in particular demonstrate that, in contrast to a centralized approach, a bottom-up regional approach can match potential supply scenarios with a particular energy demand profile, while Lovett et al. [105] and Narodoslawsky and Stoeglehner [106] demonstrate that issues related to land-use and system integration can only be decided in a particular regional context. Terrados et al. [107], Feder [108] and Ramachandra [109] identify the region as an effective unit for energy resource and system management given the ability of regional studies to synthesize broader technical and political conditions into the analytical domain while respecting local nuance and absorptive capacity. Furthermore, the regional concept is flexible and open and therefore lends itself well to multi-scalar analyses and adaptive management. The missing link, however, is in developing an approach through which to delineate regional boundaries. In some jurisdictions, existing national or sub-national administrative boundaries might suffice (e.g., the state or the district level in India as per [110] and [111], respectively), but in others such as Canada where sub-national (i.e., provincial) administrative areas can be very large, new regional bodies may need to be delineated for analytical and management purposes see [112]. Such approaches might include using pre-existing political regional units such as regional development agencies [88]; taking the major load center in an area and calculating its theoretical energy footprint see [106;156]; or scaling the analysis to include only a single power system or liquid fuel market.

Regardless of the specific approach taken, three basic principles that must be considered when identifying regional boundaries for RE analytical purposes are identified here. First, the unit of analysis must be a politically contiguous (i.e., territorial) area in order to be sensitive to incumbent levels of authority and responsibility, primarily those outlined in constitutions and which are established political and social conventions. Second, size matters. Ideally, the unit of analysis should be large enough to evaluate relevant economies of scale and base-load capacity (particularly for biomass processing facilities which may require large areas of marginal land), but also small enough to incorporate relatively high resolution data from which to evaluate local comparative advantages in system design and resource availability. In other words, it should not privilege RE development at either the centralized or the decentralized scale, but it must recognize the land intensiveness and site-specificity of RE deployment. Third, shape and orientation are critical. It is important to capture a heterogeneous landscape from which multiple resource options can be evaluated and integrated into an energy system, and to ensure that energy flows are drawn from all directions to fully represent the supply-shed.

The issues which drive and constrain RE are ultimately cross-scalar, and some political levels are best for steering, others for planning, and others for implementation. Furthermore, there are valid reasons to operate at different analytical scales to consider the unique spatial qualities of specific source-system interactions. Zubaryeva et al. [63] for example, use pre-defined 'waste-management zones' to study the feasibility of deriving biogas from municipal sources of waste given the established authority, information management schemes, and logistics that provide a strong foundation upon which a biogas industry might flourish in these zones if it were supported by higher level policy and planning toward that end. There are similar arguments to be made with respect to other RE resources: e.g., a 'watershed' approach to hydro-energy assessment or an 'urban' approach to solar energy assessment. Furthermore, [153] demonstrates how GIS can be used at the municipal level to locate new housing developments in optimal areas for micro-renewable energy generation. None of these resources and technological options are sufficient on their own, however, and a more flexible regional approach allows policy analysts to study how a mix of RE can be integrated into the landscape and in turn the fuel mix. Furthermore, as an open and flexible concept with the ability to link the global and the local, the regional concept is well suited for cross-scalar knowledge transfer and therefore the coordination of energy planning at various political and administrative levels.

3.2. Assessing spatial interactions between RE source options

No single renewable energy source is available in sufficient concentrations to satisfy regional energy needs, especially at costs acceptable to the current economic system [90,113]. A sustainable fuel-mix will include a range of sources, all of which must be recovered from a limited land base. Interaction of various RE technologies on the landscape is therefore a key factor in defining the 'net energy' available from a given RE source and in defining trade-off scenarios between different source options [14]. Where feasible, an obvious solution is to combine RE options or to combine energy and non-energy land-uses on the same land-base; what is referred to as 'hybridization' [115,116], 'synergy' [117], or 'multi-purpose schemes' [13]. When these land-preserving and energy-maximizing tactics are not feasible, decisions must be made about which source options will be given priority. Currently, there is a lack of quantitative and spatially explicit analysis which engages the issue of trade-off scenarios involving land-use conflict and land footprints in specific regional contexts [118,119], largely because RE simply has not reached a scale where these conflicts arise which makes the issue largely hypothetical. The increasing rate of local RE deployment,

however, will be a significant source of future land-use conflicts, thus presenting an important policy problem to solve.

Recently, attempts have been made to model the spatial interactions between various RE source options using GIS. The approach taken in [22] begins from the premise that RE potentials are not always additive and therefore land base is only available once. Working from this logic, the authors map the spatial distribution of various RE resources and assume that existing land cover at that site will be the selective driver for RE development. Dominguez et al. [24] take a similar approach; their method introduces siting rules early in the mapping process to ensure that more than a single energy source option is not considered within the same land base. Alternatively, and as mentioned above, in many cases RE systems do not necessarily require the exclusive use of land, and in fact RE systems can be designed to extract multiple sources of energy from the same land-base. A recent example of this synergistic logic can be found in Li et al. [120] who identify sites where solar and wind energy can be co-located to provide power at complementary intervals (i.e., solar in the day, wind at night). This ensures that solar and wind power systems operate collectively to maximize facility usage rates and thus the profitability of the overall system see also [121,122].

Given the opportunities to co-locate energy systems and thus diversify fuel-mixes while rationing land-base, a given site can not be characterized only by the energy source most likely to be liberated but must be described by the multiple energy sources that exist at that location and the relative potential of that location to support various source options. This is the difference between a binary (either/or) approach and a fuzzy approach to mapping preferred energy resources and land allocations. To be relevant to policy and planning, this logic must be spread over a broad area rather than performed on a case-by-case basis, and must include multiple source options. Exposing the geographic pattern of RE complementarity at a policy-relevant scale will more closely approximate RE potentials per unit area; elevate hybrid energy systems and multi-purpose land use schemes from the conceptual level to the planning level; and enable the design of more cost-effective procurement programs. It will also identify possible candidates for a zoning variance: i.e., locations at which municipal land use and land development rules might need to be changed to allow shared land uses.

Raster-based overlay modelling provides a useful analytical tool to achieve this goal. Using this method, regional scale constraint-based geospatial methods (as discussed above) identify the spatial distribution of exploitable energy potentials specific to various source options (in the example below, solar energy and bioenergy). These results are re-classified into an ordinal scale representing the RE potential at any given location (pixel) for the respective source option. For the sake of illustration, a scale of 0–10 is applied here, with 10 representing a site characterized by high potential of a given source option (i.e., easily accessible and high density or highly predictable energy sources), and 0 representing sites of no potential due to one or more restrictions or too many impact factors. The following algorithm is then applied[1]:

$$[\text{solar_energy}] - [\text{bioenergy}] = [\text{shared_potential}] \tag{1}$$

This algorithm is used in a pair-wise manner to produce multiple maps of shared potential. Sites (pixels) with a [shared_potential] value in the range of ± 7–10 have one RE source option that is significantly greater than the alternative. At these locations, only a detailed comparison of the technological pathways from which that specific energy source can be liberated will proceed. The closer [shared_potential] is to 0, however, the greater correlation in space of relative production potentials, and the more seriously hybrid energy systems should be considered.

Mapping shared potentials will increase the relevance and power of geo-information in two ways. First, it provides the basis to search for sites that can potentially support some of the hybrid systems discussed above. Second, it helps to forecast the point at which land-use trade-offs are inevitable. If the fuel-mix directive requires that solar energy provide a quantity of energy above that which can be recovered from sites that can only support solar energy – i.e., south-facing rooftops that are close enough to existing distribution infrastructure are saturated – solar energy infrastructure will need to sprawl. Maps of 'shared potential' offer insight into where this sprawl will impact an area's capacity to recover energy from a different source option.

3.3. Choosing among the options: geographical approaches

Technology roadmaps are not globally applicable because RE supply and conversion options are sensitive to geographical context. To choose appropriate subsidy structures or fuel mix quotas, and to invest appropriately in research and development, policymakers and planners require some understanding of those RE systems which are closer to market readiness, more competitive, and/or more appropriate for their jurisdiction. This requires a jurisdictionally-relevant technology roadmap, defined as a fuel-mix directive and a set of possible conversion technologies that are currently or potentially viable in a management area given specific geographical opportunities and constraints. Currently, however, the synthesis of spatially explicit resource assessments with in-depth evaluations of an area's technical and political absorptive capacity for a range of conversion options is lacking. In cases where multiple resource or technology options are assessed, analysts presuppose the exploitation of resources e.g., [51,123], are conservative on the technology side of the mapping exercise e.g., [24,125], or use national or global averages as inputs into detailed technology assessments. This precludes the development of forward-looking and jurisdictionally-relevant technology roadmaps that consider the current and future technological potential of RE generation within a specific area, and in turn makes it difficult to design technologically discriminate and fiscally responsible procurement mechanisms. To achieve this goal, a set of analytical techniques wherein various technological configurations can be evaluated and compared under site-specific resource conditions is required.

Since at least the 1970s mathematical computer modelling has been among the preferred modes of analysis for providing a baseline understanding of energy–economy–environment (E3) interactions [126–128]. Specifically, bottom-up engineering models dissect an energy system into its respective operational stages: i.e., primary energy availability, energy extraction processes, feedstock transportation regimes including storage if necessary, capital expenses to build the facility, operation and maintenance costs, and decommissioning/replacement values. Using this approach, each component can be evaluated separately, but when employing a systems approach they are pieced together using disaggregated data to represent them as a network of stocks and flows of energy, material, cash, and various combinations thereof to accurately model energy systems. There are a number of 'off-the-shelf' modeling programs currently employed to achieve this goal in the RE sphere [129]. While there are many ways to classify these tools, a notable distinction is between those tools which analyze specific projects (e.g., RETScreen International 4.0; the ASPEN models developed at NREL) and those which are capable of

[1] Brackets are used to signify an individual layer or map being used in the equation.

modeling integrated power systems at either the system-level (e.g., HOMER) or at the national or regional fuel-mix level (e.g., NEMS). Coupling geo-spatial data with these modeling packages delivers model outputs that better reflect the situation on the ground.

In order to compare and prioritize public investments into different conversion options, it is important to derive theoretically and practically robust criteria from these E3 models. These are known as 'measures of merit'. Typically, economic measures such as net-present value (NPV) and levelised energy costs (LEC) are privileged so that least-cost options can be chosen, thereby minimizing the burden of publicly funded procurement programs on ratepayers and taxpayers. The functional unit against which the costs of opposing options are calculated is generally the kilowatt hour or gigajoule delivered. In other words, it is common to compare energy systems on a $/MW(/MJ) basis.

Prioritizing public procurement decisions based on $/MW(/MJ) alone risks catalyzing sub-optimal decisions about which systems should be privileged in policy design because it neglects three crucial facts. First, RE policy seeks to engage multiple economic, environmental, and social objectives simultaneously. This is especially true in the context of the rhetoric and practice of 'sustainable development' and given the fact that energy policy necessarily operates at the crux of other policy domains (industrial; economic; social; environmental). Non-monetary goals are not captured in an economic or financial metric alone. This explains the trend identified by Pohekar and Ramachandran [130] toward multi-objective decision-support systems using multi-criteria analyses (MCA) see also [131,132]. Terrados et al. [107] employ a SWOT approach, whereby relevant technologies for a jurisdiction are identified and their strengths, weaknesses, opportunities, and threats are assessed based on economic, social and environmental merits. Simao et al. [79] and Ahamed et al. [78] employ participatory approaches that build upon expert analyses, such that local preferences are included in the decision-making process. Second, a $/MW(/MJ) metric fails to take seriously the fact that energy recovery from RE resources is a very land-intensive process with considerable implications on local land-use planning. The value of a RE system is not only a matter of the quantity and quality of energy it can deliver at reasonable costs, but is also a matter of the efficiency with which it can ration its primary input and that which fundamentally limits RE availability in an area: local land base [106,133]. Indeed, decision-makers need to know the local land-use implications of RE system deployment in their jurisdiction, and an area-based index such as $/MW(/MJ)/ha will help to consider this in policy design, especially for utility-scale applications which will have the greatest land footprint. This valuation will also shed a more favourable light on hybrid energy systems given that they are most likely to return a high energy-to-land ratio and thereby limit infrastructural footprints. Currently, however, issues of land uptake are insufficiently addressed in geographical analyses of RE potential, although general 'footprint accounting' methods are being developed for RE [106,134,135] that can be applied in specific regional contexts using a combination of spreadsheet analysis and GIS. The third shortcoming of a $/MJ(/MW) metric is that it focuses on costs and impacts alone, and therefore does not capture the spatially-explicit collateral benefits that can be derived from RE deployment and operation.

3.4. Mapping value for RE: the 'where to develop' question

The "where to develop" question is one of the core problems for resource geography generally [136] and is increasingly becoming a problem for energy planning more specifically [14,137]. The review above indicates geo-information techniques are increasingly used to develop constraint-based map products and geographical supply–cost curves from which the issue of site decisions or the order of resource development can be engaged. As with all other resources, those RE resources that are concentrated above some average with minimal restrictions on land use, and which are within close proximity to demand centers or infrastructure, are typically preferred. The present focus on constraints, costs, and density, however, is only capturing part of the story.

Patterns of investment are determined based on the perceived benefits of a resource option relative to its alternatives. Generally speaking, RE provides a broad range of benefits that extend beyond the delivery of energy, not the least of which is the development of a new high-technology and manufacturing industry to support economic growth and reduced atmospheric pollution. It is important to note, however, that many of these social and environmental returns on investment are not inherent but are rather a function of where the system will be located see also [138]. It is also important to note that many of the strongest contributors to the corrosion of public support (e.g., landscape amenity loss) can be mitigated simply through better spatial planning, especially when planning is done in consultation with local citizens.

Table 4
The conceptual and analytical dimensions of 'locational value'

Value category	Type of collateral benefit	Spatial signal of potential benefit	Examples from literature
Technical	Congestion management	Locational price of electricity	RE can alleviate system congestion and are closer to market value at locations where importing power supply is constrained [141,142]
	Efficient use of distribution network or system upgrading	Distance to infrastructure with available capacity; age of existing generating units	
Environmental	Greenhouse gas alleviation or 'capacity credit'	Reliance of an area (community, region) on heavy oil, low-grade coal, or other high-emitting sources	Remote community-level bioenergy facilities drawing from forest thinning operations will replace distributed diesel generating units while also reducing the local risk of forest fire hazards [143];
	Ecological impact	Extent of local unproductive land and land that is not ecologically or culturally sensitive; brown-field sites	bioenergy crops can be used to decrease leaching of specific heavy metals from contaminated sites and/or to recycle saline waste water [144]
Social	Employment	Spatial patterns of socio-economic welfare (e.g., income levels) and of local economic productivity	Locating a facility far from residential areas will reduce amenity impacts (e.g., visibility of wind turbines, traffic flow into bioenergy
	Energy poverty	Local cost of heat and electricity relative to household purchasing power; local access to clean and reliable energy resources	facilities) and thus social friction [145]; subsidizing wood pellets in a low-income rural area relying on heavy oil would not only maximize GHG abatement but also social welfare [146]
	Social friction	Local attitudes toward RES	

Geospatial analysis can be employed to identify ‘opportunity’ investments; i.e., investments which will minimize public burden and maximize collateral benefits, all while achieving a desired NPV or LEC and therefore ensuring investor confidence. This has been conceptualized elsewhere as ‘locational value’ [139]. The concept of ‘locational value’ can be used to provide a working basis from which a strategic search for acceptable and effective locations for public investment and system development might proceed, thereby facilitating a local planning approach that considers broader issues related to energy investments. These broader issues include long-term system planning (i.e., the ‘techno-economic’ dimension of value); ecological integrity (i.e., the ‘environmental’ dimension of value); and social development (i.e., the ‘social’ dimension of value). Each of these dimensions of value, what are collectively referred to as the ‘triple bottom line’, is considered in Table 4. The equal consideration of these technical and social issues in the searching and spatial planning process will help to bring greater symmetry to analytical and policy frameworks [140].

Priority areas for system deployment can be identified using any one or a combination of the indicators listed above. The indicators incorporated into geo-information products can be based on stated objectives of the procurement and deployment program and its implicit and explicit links to broader policy arenas such as social policy, environmental policy, or infrastructural policy. If, for instance, economic development is an important secondary goal of RE development, then areas where resources exist and employment levels are low should be weighted heavier in the mapping process. In the case, where these objectives are unknown to the analyst, some of the participatory techniques discussed above can be used to determine the meaning of ‘locational value’ in a specific regional or community-level context based on citizen input.

Once chosen, the indicators can be formatted into an appropriate spatial data structure, and used to extend constraint-based mapping simply by layering them into the constraint map. Sites that return a higher value on any of these indicators would therefore not only be suitable, but preferred due to added collateral benefits that can be achieved, if a system or investment is appropriately sited. If value maps are made publicly available, the searching phase for a prospective investor will be drastically decreased while the chance of project approval will increase.

In addition to making spatially-explicit connections between broader policy objectives through the identification of locational value, geo-information techniques can be used to reveal the spatial distribution of energy surplus and deficits. Mapping energy balances is a matter of estimating current and future energy consumption patterns based on demographic data and trends in urban development, and comparing consumption with potential energy yields within specific areas. The spatial distribution of surplus and deficit helps to identify areas at which further investment is most needed and to quantify and forecast the localized energy and material flows that are required to satisfy indigenous demand with indigenous sources [147,148].

3.5. Summary

This section has identified a number of analytical deficiencies associated with conventional models of geo-information management and has suggested concepts and techniques that can be used to address them through the sustained application of geographic thought and practice. First, the application of scale-aware thinking and a firm understanding of modifiable areal unit problems (and, more specifically, analytical boundary issues) will help to identify optimal scales at which RE are analyzed and best managed. Second, taking seriously issues of land-use will help to extend hybrid energy system designs from concept to planning consideration while at the same time providing the information required to forecast, assess, and communicate the scale of land-use trade-offs required to integrate RE into the regional fuel-mix. Third, employing the concept of locational value and spatial energy balances can move beyond issues of site suitability and toward firm suggestions of optimal patterns of investment and patterns of energy flows that can not only inform procurement program design, but also industry level site-searching and site-assessment.

4. Conclusions

The review above assessed the status of current research and provided a generalized set of questions, concepts, and techniques to guide future research in this area. The analysis of progress to date revealed a number of ‘off-the-shelf’ analytical techniques that can be readily applied in the RE decision-support domain. A critical assessment of this research identified ways in which information can better reflect the nature of RE. More specifically, the review highlighted the significance of scale-aware thinking and data modeling techniques; cautions against a purely techno-economic analysis; encourages researchers to consider the implications of land-use conflicts and potential means by which different RE technologies might be co-located on a single site to increase land use efficiency’; and re-orients the ‘where to develop question’ so that GIS-based decision support systems can be driven by enhanced spatial thinking about issues related to ‘land and life’ and energy-human-environment relations through identifying optimal deployment patterns [149].

There are two primary limitations to the development and application of this information management model. The first limitation is data quality, particularly in terms of precision and scale. For the purpose of RE source assessment, technology selection and deployment, data quality is in most cases insufficient and introduces considerable uncertainty into otherwise robust analytical frameworks. Decision-makers are therefore often presented with broad information – i.e., summaries of global, national, or state/provincial potentials – without a clear understanding of the underlying data—i.e., the potential and constraints that collectively define their jurisdiction’s ability to access renewable energy sources, and the political motivations/intervention required to realize its potential. Continued deployment of ground-monitoring stations and advanced data acquisition techniques through very high resolution RS would help to rectify this limitation, but this highlights the second primary limitation: RE decision support generally, and mapping exercises specifically, are typically concentrated at the state/provincial or national level and through international agencies, because these institutions are able to internalize the costs associated with the quality of research discussed here. As a result, information is presented in aggregated form and analysis of this data thus occurs at inappropriate scales. Local level governments (municipalities, counties, regions) lack the funding and human resources necessary to develop datasets that they require to support and manage RE deployment; see also [157].

To resolve issues related to data quality and scalar discordance and to build and mobilize effective geo-information infrastructures, industry partners, public authorities, and academic institutes will need to pool resources and develop knowledge-based networks within common areas of interest. Knowledge-based networking will help to alleviate the pressures associated with the capital and data intensiveness of geo-information infrastructures. Financially, this might be facilitated through cost-sharing mechanisms to build the analytical capacity and computer

networking capabilities of research institutes and to drive the application of the concepts and techniques reviewed above. Computationally, this can be facilitated through the practical application of geospatial cyberinfrastructure or 'CyberGIS' which are terms that describe fully integrated research environments that operate beyond the scope of a single institution or data user (e.g., through geospatial data portals and high-powered virtual computer labs) see [150].

In any case, decentralizing information management through advanced integration of GIS, RS and energy research are critical to bringing institutional capacity to bear on the RE transition. Fuel-mix directives and policy programs aimed at increasing the capacity of RE are not 'one-size-fits-all', but rather are shaped by local geographies. There is a clear need for jurisdictionally-relevant fuel-mix directives that reflect the availability of RE sources, technology roadmaps that are sensitive to regional conditions to ensure the most efficient use of these sources, and deployment strategies that take advantage of the local landscape and societal preferences. A geo-information infrastructure is a powerful information management model with which to address these concerns, and can therefore greatly expand institutional capacity for RE assessment and deployment and operate as a powerful lever with which to remove the barriers that prohibit the sustained deployment of renewable energy systems.

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